

# The Promise of String Cosmology \*

Robert H. Brandenberger,  
Department of Physics, Brown University, Providence, RI 02912, USA.

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## Abstract

The interplay between string theory and cosmology is very promising. Since string theory will yield a quantum theory of space-time and unify all forces of nature, it has the potential of addressing many of the conceptual problems of the current models of early Universe cosmology. In turn, cosmology is the most obvious testing ground in the effort to construct non-perturbative string theory, and can provide the crucial connection between theory and experiment/observation <sup>1</sup>.

**Early Universe cosmology** has made spectacular progress over the past two decades, driven both by a wealth of new observational data and by theoretical breakthroughs. In particular, a scenario for the very early Universe, the **inflationary Universe** scenario [2], has emerged which has led to solutions of some of the deep mysteries of standard big bang cosmology, and which has made some quite specific predictions for the geometry of the Universe and for the spectrum of cosmic microwave background (CMB) anisotropies which have been confirmed by the most recent observations [3, 4].

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<sup>1</sup>For a more technical overview of the existing approaches to connecting string theory and cosmology, the reader is referred in [1].

In spite of its success, the inflationary Universe scenario suffers from some deep conceptual problems [5] which have prevented it from achieving the status of an honest physical theory. For example, scalar-field-driven inflationary cosmology is incomplete in the same sense as the standard big-bang cosmology was: in the context of inflationary cosmology an initial singularity is inevitable, thus making it impossible to formulate a consistent initial value problem. More seriously, the successful predictions of inflationary cosmology for the spectrum of the CMB depend - in the current models of inflation in which the exponential expansion of space is driven by the potential energy of a scalar matter field - on extrapolating the physical theory into a regime where its foundations (namely classical general relativity and weakly coupled quantum field theory) are known to break down <sup>2</sup>. The Achilles heel of inflationary cosmology is the cosmological constant problem. How do we know that the unknown mechanism which cancels the vacuum energy today does not also cancel the transient vacuum energy which is required to drive inflation? Quite apart from these conceptual problems, a convincing realization of inflation in the context of our current models of particle physics based on quantum field theory is lacking.

Recent observations are also beginning to challenge some of the premises of our current cosmological models. These observations point to the existence of a dark energy component in the Universe which makes up the bulk of the energy density but which does not cluster [7, 8]. Furthermore, recent measurements and numerical simulations show a mismatch between the predicted and observed galaxy halo structures which may imply that the dark matter is not cold (see e.g. [9] and references therein).

**String (or M-) theory** is the best candidate for a unified theory of all forces and as such for a quantum theory of space-time and matter. Thus, it will resolve the conflict between quantum field theory and general relativity, and therefore it has the potential of addressing many of the open issues in early Universe cosmology. If successful in this challenge, string theory will have made an important contact with experiment/observation, and will no longer be able to be criticized for lacking a connection to data and for thus being pure mathematics rather than a physical science. The successful determination of the entropy of an extremal black hole in the context of string theory [10] is a first major success in establishing a link between string

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<sup>2</sup>This is the so-called trans-Planckian problem for inflationary cosmology [6].

theory and cosmology.

Until recently there has not been much work on the interface between string theory and cosmology. However, it has been clear since the late 1980's that string theory has the potential to solve some of the problems of standard cosmology. For example, it was argued [11], in the context of perturbative string theory, and assuming that all spatial dimensions are toroidally compactified, that as a consequence of t-duality the physics at very small radii is equivalent to that at very large radii, hence eliminating the cosmological singularities. Moreover, string winding modes may yield a mechanism which allows at most three spatial dimensions to become large, thus providing a dynamical resolution of the potential embarrassment that superstring theory is consistent only in nine (or ten in the context of M-theory) spatial dimensions. This example demonstrates that with string theory, questions about the Universe can now be addressed scientifically which before the advent of string theory were exclusively in the realm of philosophy.

In the past five years string theory has undergone a “second revolution”. With the discovery of **D-branes** [12] it has become clear that there are many more fundamental degrees of freedom than just strings. Dualities between the previously known five consistent string theories were discovered which indicate that there is a common underlying theory, **M-theory**. The different string theories (and also 11-d supergravity) correspond to certain corners of moduli space of M-theory. A further new important tool is the **AdS-CFT correspondence** [13] which relates classical gravity on an anti-de-Sitter background to a conformal field theory living on the boundary. Recently, much attention has been focused on **brane world scenarios**, scenarios based on a combination of the above ideas in which the matter fields of our Universe are confined to a three-brane and only gravity lives in the higher-dimensional bulk (see e.g. [14]). In general, the spatial dimensions transverse to the branes must be very small in order to avoid too large deviations from Newton's gravitational laws. An interesting suggestion first put forward without a direct connection to string theory [15]<sup>3</sup> is that two of the extra dimensions are large (mm scale). Since the four dimensional effective gravitational constant is related to the fundamental higher dimensional one via the size of the extra dimensions, the fundamental gravitational constant can be reduced to the TeV scale, provided the large extra dimensions have

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<sup>3</sup>See [16] for a realization of this idea in the context of string theory.

a size of the order of 1mm. This provides the potential for solving the mass hierarchy problem of elementary particle physics. By constructing models in which gravity remains confined to the brane, it is possible to make the extra dimensions large (in fact even infinite [17]).

On the other hand, there is still no non-perturbative formulation of M-theory; not even its fundamental physical degrees of freedom are known. In at least one approach to M-theory [18], the underlying theory is postulated to be a quantum mechanical matrix model. If this is true, then some of the non-commutativity of the matrix model will be reflected in non-commutativity of the space-time coordinates at a microscopic level. Returning to the more traditional description of M-theory, another serious problem results from the fact that the moduli space of vacuum states corresponding to any of the string theories is huge, and many of the predictions for particle physics as well as for cosmology depend on which vacuum state is chosen. A key challenge to string cosmology is to find a mechanism which distinguishes the vacuum state corresponding to our Universe. Since the moduli correspond to massless fields, new problems for cosmology appear: why don't we see the massless particles associated with the moduli fields, and if this question is answered in the usual way by invoking some non-perturbative mass generation for the moduli, then why don't the moduli over-close the Universe [19]?

However, even without first having to solve these difficult problems, there are interesting avenues for string cosmology. A particularly interesting issue is to determine whether there are string-specific ways to obtain a period of inflationary expansion in the early Universe. If the answer to this question is affirmative, then it is of utmost importance to try to find observational signatures which could distinguish these string-specific inflationary models from scalar-field-driven inflation. The answer to this question will inevitably require looking beyond the power spectra of density fluctuations and of CMB anisotropies, since any set of power spectra can be obtained by suitable choice of a toy model scalar field potential. It may, however, also turn out that string cosmology does not yield anything that looks like the usual inflationary scenario, but that the resulting theory nevertheless provides an alternative to inflation in solving the problems of standard big bang cosmology such as the horizon and flatness problems. This possibility is realized in the pre-big-bang approach to string cosmology [20] based on dilaton gravity as the low-energy effective theory consistent with the symmetries of string theory. In this scenario the background in the Einstein frame is in fact contracting super-

exponentially in the pre-big-bang phase, leaving an effective Hubble constant whose absolute value is increasing in time. In pre-big-bang cosmology the spectrum of scalar metric fluctuations stemming from the dilaton gravity sector is not scale-invariant as it would be in inflationary cosmology [21]. A more radical alternative to inflation which can solve the homogeneity and flatness problems is the varying-speed-of-light scenario in which the speed of light in the early stages of the evolution of the Universe is postulated to be many orders of magnitude larger than at the present time [22, 23].

Another direct observational issue which string cosmology should address concerns the origin of dark energy. Since string theory leads to a large number of scalar moduli fields, it is of great interest to explore the potential of these fields for explaining the origin of dark energy. Possibly related to this issue is the question of the smallness of the observed cosmological constant. Finally, even without knowing the exact vacuum state of string theory it should be possible to study whether string theory will indeed wash out the singularities of standard and inflationary cosmology.

Interest in string cosmology is growing. From July 24 - August 4, 2000, about 45 physicist working on string theory, non-perturbative field theory and cosmology gathered at the University of British Columbia (UBC) in Vancouver for a workshop devoted to string cosmology. This workshop was co-sponsored by the Pacific Institute for Mathematical Sciences (PIMS), the Canadian Institute for Advanced Research (CIAR) and by the APCTP. The invited participants included B. Greene (Columbia Univ.), N. Kaloper (Stanford), L. Kofman (CITA, Univ. of Toronto), D. Lowe (Brown Univ.), B. Ovrut (Univ. of Pennsylvania), S. Ramgoolam (Brown Univ.), S. Sin (Hanyang Univ.), D. Son (Columbia Univ.), P. Steinhardt (Princeton Univ.), H. Verlinde (Princeton Univ.), G. Veneziano (CERN) and A. Zhitnitsky (UBC) <sup>4</sup>. Many different approaches to string cosmology were represented at this workshop. In the following discussion of various approaches to string cosmology I will limit myself to those which were discussed extensively at the workshop.

Based on the conclusions of one of the most conservative approach to string cosmology, namely **Pre-Big-Bang Cosmology** [20], it is clear that we should expect important differences in the evolution of the early Universe in string cosmology compared to scalar-field-driven inflationary cosmology.

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<sup>4</sup>See the web site <http://kepler.physics.ubc.ca/~pfs99> for details about the workshop.

Pre-big-bang cosmology is a low energy description of physics which takes into account all of the low energy modes in string theory, i.e. not only the graviton but also the dilaton and the anti-symmetric tensor field (the latter, however, does not play an important role for the background dynamics at the level of the homogeneous equations of motion <sup>5</sup>). The symmetries and equations of motion for dilaton gravity give rise to a scenario of cosmology in which the Universe starts out in a state near the perturbative string vacuum, goes through a dilaton-driven phase of contraction during which the Hubble radius  $H^{-1}(t)$  ( $H$  being the expansion rate of the Universe and  $t$  denoting time) shrinks faster than the physical length of fixed comoving scales, thus simultaneously solving the horizon problem of standard cosmology and giving rise to a mechanism for structure formation similar as in the usual inflationary cosmologies: quantum vacuum fluctuations existing during the contraction phase on sub-Hubble lengths get frozen in when the Hubble radius becomes smaller than the wavelength of the fluctuation, they are amplified super-adiabatically while the wavelength is larger than the Hubble radius, and then re-enter the Hubble radius in the late Universe as classical density fluctuations. As the Universe contracts, the curvature increases. Eventually, in a way which unfortunately cannot be described by the equations of dilaton gravity, the Universe makes a transition to an expanding Friedmann cosmology related to the contracting phase via a duality transformation. Note that in pre-big-bang cosmology, both the background evolution and the spectrum of induced fluctuations is different from that of scalar-field-driven inflationary models. The density fluctuations from the dilaton sector are not scale invariant. In fact, they are completely unimportant on large length scales. The other fields present in pre-big-bang cosmology (such as the axion) will, however, generate fluctuations which can be scale-invariant [24]. Since these fluctuations start out as isocurvature fluctuations, they lead to different predictions for observables such as the spectrum of CMB anisotropies than the scalar metric fluctuations of inflationary cosmology. The lesson we learn is that it is quite likely that the predictions of string cosmology will differ enough from those of standard inflationary cosmology to enable observations to probe the physics of the Planck scale.

Pre-big-bang cosmology suffers from the graceful exit problem: in the con-

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<sup>5</sup>As was mentioned at the workshop, a non-vanishing tensor field decreases the set of inhomogeneous initial conditions which can lead to the pre-big-bang evolution.

text of the equations of motion of dilaton gravity, the contracting branch of the evolution terminates in a singularity, and the expanding branch emerges from an equivalent singularity. Since the singularity occurs in the high curvature regime, it is clear that the effective dilaton gravity action no longer describes the stringy physics in a correct way close to the singularity. A challenge for string cosmology is to understand if true stringy physics can solve the graceful exit problem and lead to a smooth transition from the contracting dilaton-dominated phase to the expanding phase with fixed value of the dilaton. Although there have been several attempts to go beyond dilaton gravity in order to solve the graceful exit problem (see e.g. [25] for a recent overview), there is not yet a convincing approach. An important open problem for string cosmology is to develop a truly stringy, non-perturbative version of the pre-big-bang scenario, or to find out how the scenario must be modified in order to become a truly stringy cosmological model.

Another promising approach to string cosmology is based on Horava-Witten theory [14] and is sometimes called **heterotic M-theory cosmology** [26]. The theory is based on one particular ray in the moduli space of M-theory, namely the compactification of 11-dimensional supergravity on an orbifold  $S^1/Z_2$ . This leads to two distinguished co-dimension one planes, the orbifold fixed planes. As usual, it is assumed that, in addition, six spatial dimensions are compactified on a special type of Calabi-Yau manifold, and that there is a set of  $E_8$  gauge supermultiplets on each orbifold plane. The reason for adopting this particular orbifold compactification is that it allows for chiral fermions [14]. The resulting theory is dual to the strongly coupled  $E_8 \times E_8$  heterotic string theory. Matching at tree level to the phenomenological gravitational and grand unified gauge couplings, one finds that the orbifold must be larger than the Calabi-Yau radius. This suggests that there is a regime in which the dynamics of the Universe is effectively five-dimensional. The resulting five-dimensional effective theory is a gauged  $N = 1$  supergravity coupled to four-dimensional boundary gauge and matter supermultiplets (see e.g. [27] for a recent survey). Initially, only the effective four-dimensional equations were studied. However, it has recently been realized that the dynamics in the orbifold direction is quite nontrivial and may lead to new effects of great interest to cosmology. In particular, the equations of motion in five dimensions admit as a static solution a pair of three-branes parallel to the orbifold fixed planes. It is tempting to try to obtain inflation from the nontrivial dynamics involving the orbifold direction. Note, however,

that as in pre-big-bang cosmology, many truly stringy effects are frozen out in the effective action-based analysis of heterotic M-theory cosmology.

A rather different approach to string cosmology is based on proceeding in analogy to the usual starting point of big bang cosmology, which is the assumption that the Universe starts out with Planck size and emerges from a hot initial state in which all degrees of freedom were highly excited. It seems quite natural to generalize this starting point to string cosmology and to assume [11] that the Universe starts out with all spatial dimensions of string scale and all fundamental degrees of freedom excited according to their thermal distribution. In particular, this means that the winding modes of strings and branes are highly excited. This approach is called the **brane gas approach** to string cosmology. In this approach, all spatial dimensions start out compact and the question for cosmology is not why certain dimensions are compactified, but why a fixed number of dimensions can dynamically decompactify (in the sense of their radii becoming larger than the present Hubble radius of the Universe). There have been some interesting recent developments [28, 29] along the lines of this approach to string cosmology. In particular, assuming that all spatial dimensions are compactified on a torus, it has been shown that whereas at early times (small sizes) the higher dimensional branes dominate the evolution, it is the fundamental strings which have the most important effect at late times [30]. Thus, the mechanism of [11], which only allows three spatial dimensions to become large, survives in the modern view of string theory. In addition, the duality under inversion of the radius of the torus is maintained, thus assuring that no physical cosmological singularities will arise. It is important to generalize these considerations to more realistic background spaces.

The approach to string cosmology which at the present time is attracting most attention is the class of **brane-world scenarios** (see e.g. [31] for work along these lines presented at the APCTP/CIAR/PIMS string cosmology workshop). The starting point of this approach is the assumption that our matter fields are confined to a three-brane (four space-time dimensions) embedded in a higher-dimensional (usually five-dimensional) bulk space-time. An important realization is that it is possible [17] to confine gravity on one of the branes by having the four-dimensional metric depend on the fifth coordinate (the orbifold coordinate in the language of heterotic M-theory cosmology). In many cases, the bulk metric is AdS, and this gives rise to a tantalizing connection with the AdS-CFT correspondence. However, most



work along these lines is not directly justified from string theory. There appear to be an unlimited number of versions of the basic scenario. As was stressed at the APCTP/CIAR/PIMS string cosmology workshop, an urgent task for string cosmology is to derive the basic rules which a brane-world scenario must obey if it is to emerge from string theory. Is the brane an orbifold fixed plane (as it is in heterotic M-theory cosmology) or is it a D-brane? How many branes are there in the scenario? Are there matter fields in the bulk? At the present time, most work on brane-world cosmology is based on studying the background gravitational equations of motion of the brane in the presence of the bulk, making use of the general relativistic Israel matching conditions. It has been realized that the equations for the dynamics of our brane in the brane-world scenario may be quite different from the usual four-dimensional general relativistic equations. This provides stringent constraints on brane world cosmologies. However, it also provides the chance to obtain new effects, or to provide new sources of inflation. In order to make contact with the wealth of recent cosmological observations on the distribution of light and CMB light, it is crucial to extend the theory of cosmological perturbations, the basis for making such a contact, from the usual four-dimensional setting to the brane-world scenarios. Initial work along these lines was presented at the workshop (see [32] and references therein). A limitation which the brane-world scenarios share with some of the other approaches to string cosmology is that most of the analysis is based on a truncation of the dynamics to low energy modes, thus eliminating many truly stringy effects. It is, however, possible to obtain interesting new effects for cosmology. For example, if our Universe is a three-brane moving in a bulk black hole background, it is possible [34] to find a realization of the varying light scenario for solving the problems of standard cosmology.

Ultimately, however, a complete cosmological model should be based on the non-perturbative formulation of M-theory. Starting from the matrix theory approach to M-theory (see e.g. [18, 33]), it seems likely that the resulting space-time theory will be non-commutative at the string scale (see e.g. [35] for work along these lines presented at the workshop). One limitation of the matrix theory approach to M-theory [36] is that the theory is at the present time only defined in light-cone coordinates, which makes the connection to a space-time formulation very challenging.

A generic problem which appears in all approaches to string cosmology is the moduli problem. What freezes the value of the dilaton and what sets

the scale of the extra dimensions? Usually it is assumed that some non-perturbative physics is responsible for the answers. If an effective potential provides the required mechanism (see e.g. [37] for some recent work presented in Vancouver), then why does the value of the potential at its minimum not lead to another source for the cosmological constant? Thus, the moduli problem and the cosmological constant problem appear to be related. There are some new approaches to solving the cosmological constant problem based on the brane-world scenario, e.g. a model by Verlinde [38] in the context of a theory with two branes, the physical brane and the Planck brane, which assumes that the cosmological constant on the Planck brane is protected by supersymmetry, and that it flows to a small cosmological constant on the physical brane via renormalization group flow.

The field of string cosmology is still in its infancy. Although many interesting approaches to connecting string theory and cosmology exist, most of them suffer from our ignorance about the true non-perturbative formulation of string theory. The promises of the field, however, are great, as witnessed by the excitement expressed at the APCTP/CIAR/PIMS string cosmology workshop

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